DETERMINING OPTIMAL TRAILER DUTY AS A FUNCTION OF USE AND AGE

MBTC 2017

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Project MBTC 2017

Final Report

By

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January 2002
University of Arkansas

EXECUTIVE SUMMARY

The distribution of fresh and frozen foods requires the use of refrigerated trailers. In addition, Reliability and Maintainability (RAM) is an important issue in the operation of refrigerated trailer fleets. Often, as trailers age, their reliability decreases. This study explores the optimization of refrigerated trailer retirement and job assignment under consideration of container aging and usage. By achieving this objective, Tyson and other organizations that operate similar refrigerated transportation systems know when to retire the trailers and how to assign trailer duty. Also, a better understanding of RAM performance of refrigerated trailer fleets is obtained.

We began by collecting maintenance history for 195 trailers. The data covers the period January 1, 1994 to March 2, 2001. We categorized the trailers as a series system comprised of five major subsystems: refrigeration, engine, tire, wheel assembly, and structure. Next, from the maintenance history data, time between failure data for each subsystem for each trailer was collected.

Given the time between failure data, we used the Weibull ++ software package and maximum likelihood estimation to model the reliability performance of refrigerated trailers. Where appropriate consecutive failure numbers (1^{st} failure, 2^{nd} failure, ...) were combined into a single probability distribution model. For each set of failure numbers, either a Weibull or exponential probability distribution was fitted to the data.

Finally, a discrete-event simulation model was developed and used to evaluate Tyson's trailer retirement policy and trailer duty. The trailer retirement policy analysis was based on total maintenance costs, salvage value, and purchase costs for a trailer. Results show that the total annual cost is minimized if the trailer is retired after 7 years of service. Retirement policies 8 years and beyond were not considered in this research because the probability distributions used to model trailer reliability was limited to the 7-year data collection period. In the trailer duty analysis, analysis tables were created to be used as a guideline for the fleet manager to compare trailers of any age based on total maintenance costs and the total number of failures. Also, using the raw data, the actual number of trailers in each percentile was created. The two analysis tables and the actual number of trailer in each percentile table are provided as shown below.

Expected Life-to-Date Total Number of Failures for Given Percentile

Year	Percentile								
	1%	5%	10%	25%	50%	75%	90%	95%	99%
1	0	0	0	0	1	2	3	4	6
2	1	2	2	4	5	7	9	10	13
3	4	5	6	8	10	13	16	17	20
4	7	9	10	13	16	19	22	24	28
5	10	14	15	18	22	26	29	31	36
6	15	19	21	24	28	33	36	39	43
7	20	25	27	30	34	39	43	46	49

Expected Life-to-Date Total Maintenance Costs ($) for Given Percentile

Year	Percentile								
	1%	5%	10%	25%	50%	75%	90%	95%	99%
1	$0	$0	$0	$0	$528	$1,881	$5,506	$9,883	$16,535
2	$37	$420	$768	$1,728	$3,339	$6,614	$11,937	$15,855	$24,066
3	$888	$1,961	$2,692	$4,224	$6,783	$11,540	$17,820	$22,081	$30,277
4	$2,477	$3,725	$5,118	$7,153	$10,642	$16,422	$23,829	$27,974	$35,561
5	$4,339	$6,407	$7,807	$10,658	$14,794	$20,856	$29,176	$33,886	$41,649
6	$6,779	$9,013	$10,415	$13,968	$18,941	$26,025	$33,708	$38,550	$47,827
7	$9,110	$11,666	$14,053	$17,466	$23,262	$30,733	$39,152	$44,207	$54,416

Actual Number of Trailers for Given Percentile (Raw Data)

<table>
<tr><th rowspan="2">Year</th><th colspan="9">Percentile</th></tr>
<tr><th>1%</th><th>5%</th><th>10%</th><th>25%</th><th>50%</th><th>75%</th><th>90%</th><th>95%</th><th>99%</th></tr>
<tr><td>1</td><td colspan="4">78</td><td>56</td><td>35</td><td>17</td><td>7</td><td>2</td></tr>
<tr><td>2</td><td>13</td><td colspan="2">29</td><td>19</td><td>53</td><td>47</td><td>12</td><td>16</td><td>6</td></tr>
<tr><td>3</td><td>8</td><td>5</td><td>25</td><td>37</td><td>40</td><td>33</td><td>24</td><td>15</td><td>8</td></tr>
<tr><td>4</td><td>6</td><td>6</td><td>11</td><td>36</td><td>42</td><td>35</td><td>26</td><td>18</td><td>15</td></tr>
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<tr><td>7</td><td>7</td><td>11</td><td>9</td><td>21</td><td>33</td><td>41</td><td>30</td><td>21</td><td>22</td></tr>
</table>

1. INTRODUCTION

The transportation of fresh and frozen foods requires timely delivery and maintained product integrity at a minimized cost. Certainly, Reliability and Maintainability (RAM) is an important issue in the operation of many types of equipment, including refrigerated trailer fleets. Often, equipment is subject to deterioration with usage and age. System deterioration is often reflected in higher operations costs and lower fleet performance. To keep operation costs down while maintaining good fleet performance, RAM analysis can be used to assist in managing the fleet. For example, the decision about when to replace a unit of equipment (system) or when to change its duty is a classic problem facing a fleet manager.

Vehicle fleet retirement policies have been extensively discussed in the literature. Simms et al (1984) discuss a bus replacement problem for an urban transit authority that operates about two thousand old and new buses. The newer buses are used to supply the base demand, and older buses are used to match peak demands. The main objective of this study is to determine the optimal operating and disposing policy for the mix of old and new buses. Another aim of the analysis is to select buying, selling, and operating policies to minimize the total discounted cost over a finite planning horizon. The authors develop a non-linear optimization model and dynamic programming is the solution technique.

Love et al (1982) investigate two economic replacement policies for a Postal Canada vehicle fleet. The first policy is a simple group replacement policy - vehicles are replaced based on pre-set age or mileage. All repair and replacement costs are determined for each value of the aging parameter (years or mileage). From this research, they use average discounted costs to determine an optimal replacement cycle time. The second policy is a repair limit policy - vehicles are replaced whenever they require a repair for which the cost exceeds a set limit. They model the repair limit problem as a Markov decision process. According to the authors, the steady-state repair limits can be determined by using modified Howard's policy improvement routine (qtd. in Howard, 1960), which allows a search procedure to determine the optimal limits. The authors have shown that the repair limit policy is sensitive to the discounted rate - the lower the discounted rate, the faster vehicles are replaced from the fleet. Finally, they conclude that the repair limit policy is better than the simple group replacement policy because the simple group replacement policy does not take into account the possibility that a vehicle, though not yet having arrived at the prescribed replacement age, suffers an irreparable breakdown.

Bell and Mioduski (1976) evaluate the life of a fleet of U.S. Army trucks. There are two objectives in this study. The first objective is to determine the age/mileage at which the trucks should be replaced. The second objective is to determine the economics of overhauling the fleet in order to extend its life. The authors conducted two major analyses. The first analysis is a cost analysis to determine how maintenance costs vary as truck mileage increases. From this analysis, the mileage at which the average system cost per mile is at a minimum can be determined. The purpose of the second analysis is to analyze the reliability, availability, and maintainability characteristics of the fleet. In analyzing the unscheduled maintenance actions (the reliability analysis), a Weibull failure rate function is applied. In the availability analysis, the authors study the Inherent Readiness Analysis as truck mileage increases. Finally, in the maintainability analysis, the authors determine the impacts of working hours for maintenance and major component replacements as a function of mileage.

1.1 Project Description and Objectives

The transportation of fresh and frozen products requires the use of refrigerated trailers. Tyson Foods, Inc. uses approximately 7000 refrigerated trailers to distribute fresh and frozen foods throughout the United States. Like many other systems, refrigerated trailers are subject to failure, repaired upon failure, and subjected to preventive maintenance. Tyson's maintenance department personnel perform most of the maintenance for the refrigerated trailers. Operation and maintenance of the refrigerated trailers is an integral factor in the performance of the distribution system. As the age of refrigerated trailers increases, their reliability performance may decrease. This possibility leads this study to evaluate Tyson's trailer retirement policy and trailer assignment/duty. There are three objectives of this research. They are:

- To collect maintenance history data from the Tyson refrigerated trailer fleet
- To model the RAM performance of the fleet
- To use this model to evaluate Tyson's trailer retirement and trailer duty assignment policies.

By achieving these objectives, Tyson and other organizations that operate similar refrigerated transportation systems will have a better knowledge of when to retire the trailers and how to assign trailer duty. Also, a better understanding of RAM performance of refrigerated trailer fleets will be obtained.

2. METHODOLOGY

This research presented evolved through three successive phases. In this chapter, the three phases are presented. Detailed descriptions of the data collection, fleet performance modeling, retirement policy and trailer duty evaluation are provided.

2.1 Data Collection

In order to study the RAM behavior of the Tyson fleet, we first needed to collect the maintenance history from Tyson. The complete maintenance history on trailers put in service in 1994 –1995 was collected. The raw content of the maintenance history data was reviewed. The data needed in this research includes the trailer "put-in-service" date, repair dates, the types of repair, PM dates and types, and the end date for data collection. Next, a system structure for a refrigerated trailer is defined based on the maintenance history data. The goal is to model a refrigerated trailer as a series system. Finally, the time between failure data for each subsystem on each trailer is collected.

Figure 2.1 includes an example of maintenance history data for a hypothetical 2-subsystem trailer. This data includes the date of each failure for each subsystem, as well as the start and end dates for data collection. Figure 2.2 contains the time between failure data for subsystem 1 taken from Figure 2.1. For example, the first time between failures for subsystem 1 in trailer 1 is 51 days (difference between 01/30/94 and 03/22/94), and the second time between failures is 230 days (difference between 11/07/94 and 03/22/94). The third time between failures is censored (the third failure has not occurred), which is indicated with "S". However, we do know that the third time between failures is at least 559 days. A data set of this type was constructed for each trailer subsystem.

Figure 2.1: Example Maintenance History Data

Trailer 1

Date	Subsystem	Event	Failure
01/30/94	n/a	Trailer put in service	n/a
03/22/94	1		Recap
09/23/94	2		Brake
11/07/94	1		New Tire
01/10/95	2		Brake
05/19/96	n/a	Data collection end date	n/a

Trailer 2

Date	Subsystem	Event	Failure
01/30/94	n/a	Trailer put in service	n/a
07/02/94	1		New tire
10/03/94	1		Recap
11/17/94	1		New tire
01/10/95	2		Brake shoes
05/19/96	n/a	Data collection end date	n/a

Figure 2.2: Example Time Between Failure Data for Subsystem 1

Trailer	Subsystem	1st Failure	2nd Failure	3rd Failure	4th Failure
1	1	51	230	559 S	
2	1	153	93	45	549 S

2.2 Fleet Performance Modeling

For each subsystem data set, the Weibull ++ software package is used to fit a probability distribution to the actual 1st failure data, 2nd failure data, 3rd failure data, and so on. Maximum likelihood estimation is used to fit a Weibull distribution to each failure number. Ninety five percent confidence intervals on the shape parameter (β) are used to determine if the hazard functions increase ($\beta > 1$), decrease ($\beta < 1$), or remain constant over time ($\beta = 1$). Where appropriate, consecutive failure numbers are combined into a single probability distribution model. Finally, the individual subsystem models are combined into a trailer-level model.

2.3 Retirement Policy and Trailer Duty Evaluation

Currently, Tyson's trailer retirement policy is to retire a trailer after 7 years of service. In order to evaluate Tyson's trailer retirement policy, the modeling methodologies developed in the previous sections were used in conjunction with a discrete-event simulation model and costs analysis.

3. RESULTS AND DISCUSSION

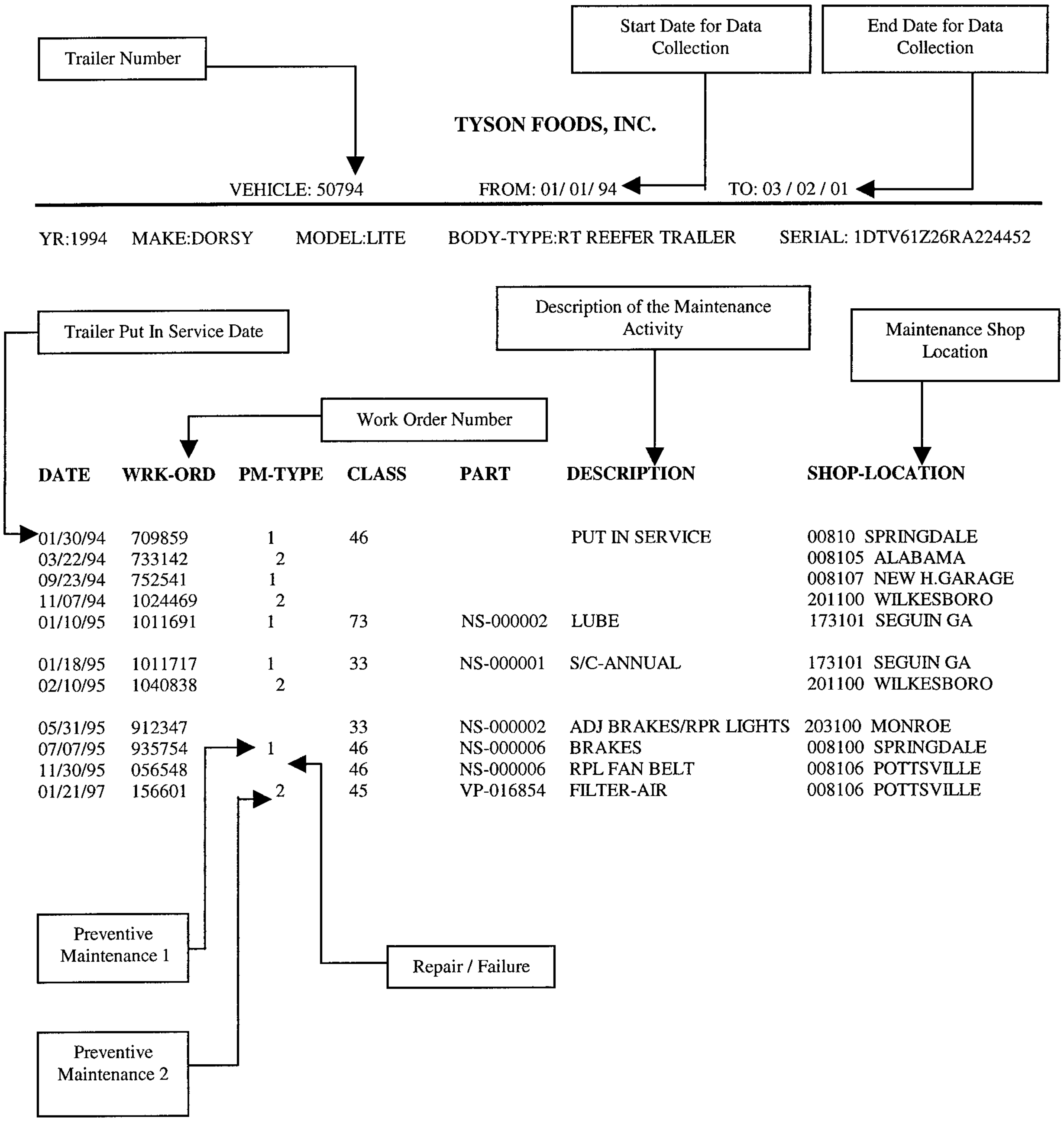
In this chapter, the results of the research are presented. Detailed results of the data collection, fleet performance modeling, and retirement policy and trailer duty evaluation efforts are provided.

3.1 Data Collection

To model the reliability performance of refrigerated trailers, maintenance history for 195 trailers in Tyson's fleet trailers was collected. The data covers the period January 1, 1994 to March 2, 2001. Of the 195 trailers analyzed, eight trailers were put into service in 1995, and 187 trailers were put into service in 1994. An example of Tyson's reefer trailer maintenance history can be found in Figure 3.1.

The maintenance history for a given trailer can be divided into three major sections that contain important information. The first section contains the trailer number, the start date for data collection and the end date for data collection. The second section contains the year, model, type, and serial number of the trailer. The third section is the detail of the trailer's maintenance history. In this third section, the first column contains the dates associated with the trailer's preventive maintenance (PM) and repair activities. The second column contains the work order number for each maintenance action. The third column denotes the type of maintenance action - 1 denotes the type 1 preventive maintenance (PM 1), 2 denotes type 2 preventive maintenance (PM 2), and a blank indicates a repair action. The fourth and the fifth columns contain the class and the part number.

Figure 3.1: Example Maintenance History



TYSON FOODS, INC.

VEHICLE: 50794 FROM: 01/ 01/ 94 TO: 03 / 02 / 01

YR:1994 MAKE:DORSY MODEL:LITE BODY-TYPE:RT REEFER TRAILER SERIAL: 1DTV61Z26RA224452

DATE	WRK-ORD	PM-TYPE	CLASS	PART	DESCRIPTION	SHOP-LOCATION
01/30/94	709859	1	46		PUT IN SERVICE	00810 SPRINGDALE
03/22/94	733142	2				008105 ALABAMA
09/23/94	752541	1				008107 NEW H.GARAGE
11/07/94	1024469	2				201100 WILKESBORO
01/10/95	1011691	1	73	NS-000002	LUBE	173101 SEGUIN GA
01/18/95	1011717	1	33	NS-000001	S/C-ANNUAL	173101 SEGUIN GA
02/10/95	1040838	2				201100 WILKESBORO
05/31/95	912347		33	NS-000002	ADJ BRAKES/RPR LIGHTS	203100 MONROE
07/07/95	935754	1	46	NS-000006	BRAKES	008100 SPRINGDALE
11/30/95	056548		46	NS-000006	RPL FAN BELT	008106 POTTSVILLE
01/21/97	156601	2	45	VP-016854	FILTER-AIR	008106 POTTSVILLE

Based on the class and part number, Tyson personnel can track which facility or service center recorded the maintenance activity. The sixth column contains a description of the maintenance activity. The last column contains the shop location where the maintenance activity took place.

Tyson performs two types of preventive maintenance (PM 1 and PM 2) on the reefer trailers and trucks. Tyson's maintenance division performs PM 1 every month for the trailers and every 7000 miles for the trucks. They perform PM 2 every three months for the trailers and every 21,000 miles for the trucks. PM 1 and PM 2 are identical except for an oil change included with PM 2. Figure A.1 in Appendix A is Tyson's PM Inspection and Worksheet for trucks and trailers.

After reviewing the maintenance data for content, we categorized the trailer as a series system comprised of six major subsystems. The six major subsystems are: refrigeration, engine, tire, wheel assembly, electrical, and structure.

Figure 3.2: Six Major Subsystems for Refrigerated Trailer in Series System

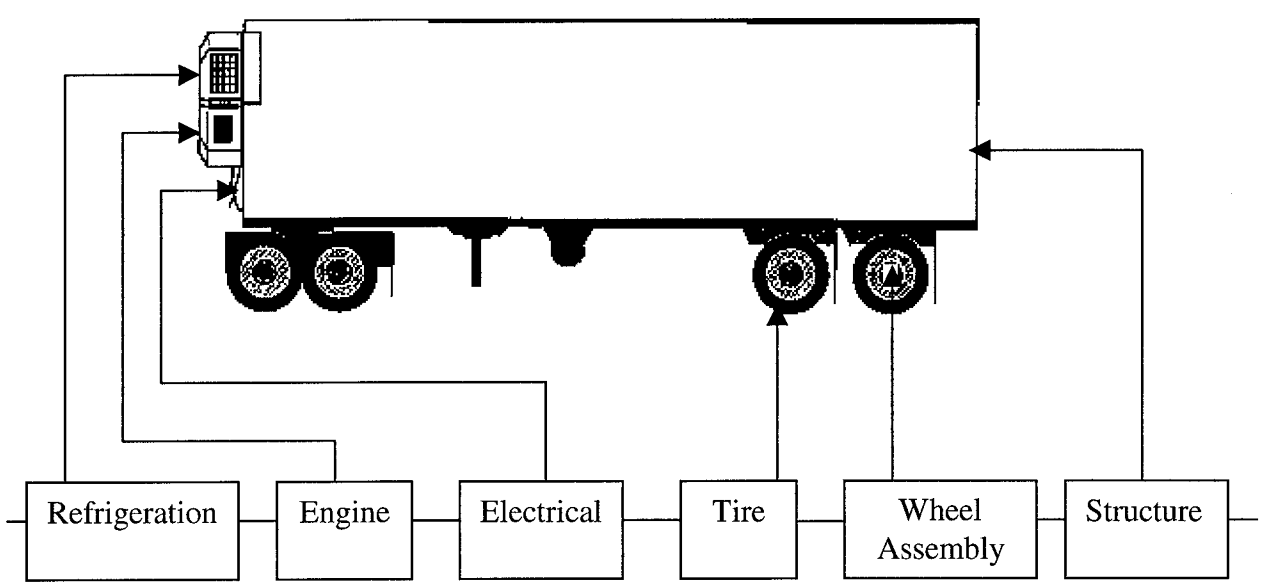


Figure 3.2 shows the six major subsystems for the refrigerated trailer in series system.

- Refrigeration subsystem consists of the components that need to be used in the operation of the refrigeration system, such as compressor, evaporator, condenser, etc.
- Engine subsystem consists of the components that need to operate the refrigeration system such as battery, motor, water pump, etc.
- Electrical subsystem consists of all the electrical components such as electrical wires, bulb, lights, etc.
- Tire subsystem consists of the mount and dismount process, valve stem, and tires.
- Wheel Assembly consists of all the brake components such as brake shoes, bearing, brake drums, wheel casing, etc.
- Structure consists of inside and outside structures of the trailer, door, air chute, mud flaps, etc.

All the components associated with the six subsystems can be found in Table A.1 in Appendix A.

Next, we enumerated the failure types for each subsystem. The failure types associated with the six major subsystems can be found in Table A.1 in Appendix A. The maintenance history for all 195 trailers was summarized using the format shown in Table 3.1 (Table 3.1 is a summary of the history for trailer 51072). Only failures were included in this summary. This data includes the start date for data collection, the date of each failure for each subsystem, and the end date for data collection.

Table 3.1: Maintenance History Data for Trailer 51072

Put in Service date: 8/26/94 Data collection end date: 03/02/01

Date of Failure	Subsystem	Date of Failure	Subsystem
10/27/94	Tire	07/07/99	Refrigeration
10/28/94	Tire	08/02/99	Tire
08/19/95	Tire	09/17/99	Engine
08/22/95	Electrical	10/18/99	Engine
11/18/95	Refrigeration	11/02/99	Tire
11/20/95	Wheel assembly	03/31/00	Engine
02/08/96	Tire	04/02/00	Structure
03/28/96	Wheel assembly	05/11/00	Tire
05/14/96	Structure	09/19/00	Engine
07/11/96	Wheel assembly	09/28/00	Wheel assembly
12/06/96	Tire	10/15/00	Tire
12/06/96	Structure	12/17/00	Engine
02/11/97	Tire	12/28/00	Tire
04/15/97	Tire		
06/17/97	Tire		
08/07/97	Tire		
10/04/97	Engine		
11/29/97	Tire		
12/02/97	Tire		
12/21/97	Tire		
12/21/97	Wheel assembly		
01/04/98	Tire		
02/13/98	Engine		
02/13/98	Wheel assembly		
06/21/98	Tire		
02/04/99	Tire		
05/27/99	Tire		
06/25/99	Refrigeration		

From the maintenance history data, time between failure data for each subsystem for each trailer was collected. The time between failures was measured using elapsed calendar time. As an example, Table 3.2 shows the time between failure data for trailer 51072's tire subsystem. Note that 21 failures occurred, the time of 21st failure is not the end date, and the 22nd failure time is right-censored, in other words, 67 days have passed since the 21st failure occurred, but the 22nd failure has yet to occur.

Table 3.2: Time Between Failure Data for Trailer 51072's Tire Subsystem

Failure	Time of Failure (days)	Time Between Failure (days)
1	62	62
2	63	1
3	358	295
4	531	173
5	833	302
6	900	67
7	963	63
8	1026	63
9	1077	51
10	1191	114
11	1194	3
12	1213	19
13	1227	14
14	1395	168
15	1623	228
16	1735	112
17	1802	67
18	1894	92
19	2085	191
20	2242	157
21	2361	74
22	2383 *	67 (S)

* - End of Data Collection
S - Right-censored (suspended)

For each subsystem, time between failure data sets were created. Table 3.3 shows a portion of the time between failure data the refrigeration subsystem. For each data value, F denotes an actual time between failure and S denotes a right-censored time between failure. For example, trailer number 50794 has experienced 4 failures. However, trailer number 50812 has experienced only one refrigeration subsystem failure.

Table A.2 in Appendix A includes the complete time between failure data for the refrigeration subsystem. Note that similar data sets were constructed for the other subsystems.

Table 3.3: Example Time Between Failure Data for Refrigeration Subsystem

Trailer Number	1st Failure		2nd Failure		3rd Failure		4th Failure		5th Failure		6th Failure	
50794	524	F	11	F	1230	F	227	F	596	S		
50796	365	F	365	F	872	F	26	F	787	F	148	S
50798	2596	S										
50800	637	F	82	F	1699	F	158	S				
50802	2612	S										
50804	954	F	716	F	571	F	261	F	104	S		
50806	627	F	72	F	199	F	25	F	1536	F	25	S
50808	274	F	2073	F	221	F	18	S				
50812	608	F	1998	S								
50814	1809	F	751	S								
50816	654	F	1941	S								
50818	212	F	222	F	126	F	2004	S				
50820	1018	F	911	F	677	S						
50822	333	F	1793	F	480	S						
50824	2588	S										
50826	2591	S										
50828	811	F	805	F	990	S						

At this point, the electrical subsystem was eliminated from consideration because only one electrical subsystem failure occurred during the 7-years data collection period. Thus, the electrical subsystem is assumed to be perfectly reliable (reliability equal to one). So, the revised trailer model is a series system comprised five subsystems.

3.2 Fleet Performance Modeling

The purpose of the next phase of this research was to model the reliability performance of a refrigerated trailer. The first step in this phase was to construct probability models corresponding to each set of time between failure data. Initially, we attempted to use the Weibull distribution to model the performance of each subsystem. The Weibull distribution was chosen because it is the most widely used lifetime distribution due to its flexibility in modeling components with increasing, decreasing, or constant hazard functions. Also, many mechanical components exhibit increasing failure rates during their lifetimes (Elsayed, 1996).

We used the Weibull ++ software package and maximum likelihood estimation to fit a Weibull distribution to each failure number (1^{st}, 2^{nd}, ...) within each subsystem time to failure data set. The shape parameter (β) and scale parameter (η) of the Weibull distribution for each failure number within each subsystem were estimated. In addition, 95% confidence intervals on β were used to determine if the hazard function is increasing ($\beta > 1$), decreasing ($\beta < 1$), or constant ($\beta = 1$). Tables 3.4 - 3.8 show the estimated values of β and η as well as the corresponding 95 % confidence intervals for β for each of the five subsystems.

Table 3.4: Weibull Distribution Parameters for Engine Subsystem

Failure Number	β			η
	Lower 95% C.I.	Estimate	Upper 95% C.I.	Estimate
1	1.6350	1.8282	2.0443	969.0681
2	0.8888	0.9983	1.1215	432.8821
3	1.0782	1.2163	1.3722	449.7208
4	0.9020	1.0264	1.1680	341.8529
5	0.7071	0.8195	0.9498	340.8895
6	0.7015	0.8451	1.0181	415.7143
7	0.6893	0.8806	1.1250	327.5526
8	0.7117	0.9561	1.2845	262.6713
9	0.6967	1.1126	1.7768	319.9364
10	0.4627	0.9388	1.9049	503.2325
11	0.5153	1.3438	3.5041	87.8272
12	0.2019	1.1550	6.6083	417.0540

Table 3.5: Weibull Distribution Parameters for Refrigeration Subsystem

Failure Number	β			η
	Lower 95% C.I.	Estimate	Upper 95% C.I.	Estimate
1	1.2035	1.3594	1.5355	1385.1115
2	0.7153	0.8313	0.9661	1096.0116
3	0.7204	0.8660	1.0409	836.6606
4	0.6405	0.8213	1.0532	834.1801
5	0.9280	1.2756	1.7532	607.3153
6	0.6149	0.9266	1.3962	381.2062
7	0.3916	0.8163	1.7015	482.6098
8	0.5854	1.8990	6.1595	559.7014

Table 3.6: Weibull Distribution Parameters for Structure Subsystem

Failure Number	β			η
	Lower 95% C.I.	Estimate	Upper 95% C.I.	Estimate
1	1.1395	1.3363	1.5671	2510.3095
2	0.5562	0.7183	0.9276	3093.1565
3	0.4901	0.7656	1.1959	3004.0838
4	0.1586	0.8643	4.7105	10345.9000

Table 3.7: Weibull Distribution Parameters for Tire Subsystem

Failure Number	β		η	
	Lower 95% C.I.	Estimate	Upper 95% C.I.	Estimate
1	1.8309	2.0300	2.2514	494.5900
2	1.1084	1.2400	1.3780	204.6300
3	0.8969	1.0000	1.1238	186.7300
4	0.9917	1.1100	1.2397	186.0000
5	0.9734	1.0900	1.2151	144.6700
6	0.9988	1.1200	1.2476	133.3800
7	1.0091	1.1300	1.2653	119.3100
8	0.8834	0.9900	1.1000	103.1200
9	0.8932	0.9963	1.1113	94.2000
10	0.8424	0.9400	1.0436	107.1900
11	0.9482	1.0600	1.1845	98.8400
12	0.9558	1.0700	1.1940	113.5700
13	0.8189	0.9200	1.0292	113.8700
14	0.9697	1.1000	1.2366	109.4300
15	0.9038	1.0300	1.1792	114.5800
16	0.9310	1.0700	1.2229	105.8500
17	0.8106	0.9400	1.0859	106.0500
18	1.0307	1.2100	1.4157	107.8700
19	0.8673	1.0400	1.2560	114.9900
20	0.9513	1.1700	1.4339	118.5000
21	0.8602	1.0900	1.3756	136.0400
22	0.6620	0.8900	1.2029	106.7800
23	0.8596	1.2000	1.6827	111.0100
24	0.6959	1.0400	1.5683	92.6500
25	0.7818	1.2000	1.8463	105.2100
26	0.6481	1.2600	2.4614	59.9700
27	0.2848	0.7400	1.9062	162.8300
28	0.2621	1.3200	6.6294	120.8200

Table 3.8: Weibull Distribution Parameters for Wheel Assembly Subsystem

Failure Number	β Lower 95% C.I.	β Estimate	β Upper 95% C.I.	η Estimate
1	1.9451	2.1492	2.3748	635.1115
2	1.0495	1.1710	1.3066	371.7639
3	1.0881	1.2156	1.3581	321.4166
4	1.0347	1.1606	1.3018	348.9263
5	0.9861	1.1083	1.2457	319.7483
6	0.9864	1.1202	1.2721	298.7134
7	0.9725	1.1124	1.2724	253.2032
8	0.9801	1.1598	1.3725	287.2551
9	0.9368	1.1381	1.3826	270.3889
10	0.9559	1.2099	1.5313	201.8676
11	0.7517	1.0166	1.3748	144.0240
12	0.6194	0.884	1.2617	223.9275
13	0.5823	1.0621	1.9372	301.3434
14	0.4465	1.0275	2.3645	141.3794
15	0.3196	0.7853	1.9297	61.6938
16	0.7793	2.2797	6.6689	66.9286

The results for all the subsystems indicate, that with the exception of the first failure, β is very close to 1.0. When $\beta = 1$, the Weibull distribution is equivalent to the exponential distribution. Thus, Weibull ++ was used to estimate the exponential parameter λ (with 95% confidence intervals) for all failure numbers greater than one for all subsystems. Tables 3.9 - 3.13 contain these results.

Table 3.9: Exponential Parameter Estimation for Engine Subsystem

Failure Number	Lower 95% C.I.	Estimated λ	Upper 95% C.I.
2	0.0020	0.0023	0.0027
3	0.0020	0.0023	0.0027
4	0.0025	0.0030	0.0035
5	0.0024	0.0028	0.0034
6	0.0020	0.0025	0.0031
7	0.0024	0.0032	0.0044
8	0.0028	0.0040	0.0057
9	0.0018	0.0031	0.0055
10	0.0009	0.0021	0.0046
11	0.0044	0.0137	0.0425
12	0.0003	0.0021	0.0150

Table 3.10: Exponential Parameter Estimation for Refrigeration Subsystem

Failure Number	Lower 95% C.I.	Estimated λ	Upper 95% C.I.
2	0.0008	0.0009	0.0011
3	0.0010	0.0012	0.0015
4	0.0009	0.0013	0.0017
5	0.0011	0.0017	0.0026
6	0.0016	0.0029	0.0051
7	0.0011	0.0027	0.0065
8	0.0006	0.0023	0.0092

Table 3.11: Exponential Parameter Estimation for Structure Subsystem

Failure Number	Lower 95% C.I.	Estimated λ	Upper 95% C.I.
2	0.0003	0.0004	0.0006
3	0.0003	0.0004	0.0007
4	0.00002	0.0001	0.001

Table 3.12: Exponential Parameter Estimation for Tire Subsystem

Failure Number	Lower 95% C.I.	Estimated λ	Upper 95% C.I.
2	0.0046	0.0053	0.0061
3	0.0047	0.0054	0.0062
4	0.0049	0.0056	0.0065
5	0.0062	0.0072	0.0083
6	0.0068	0.0079	0.0090
7	0.0077	0.0088	0.0101
8	0.0084	0.0097	0.0112
9	0.0093	0.0107	0.0123
10	0.0079	0.0091	0.0106
11	0.0091	0.0105	0.0121
12	0.0080	0.0093	0.0107
13	0.0074	0.0086	0.0100
14	0.0081	0.0095	0.0111
15	0.0076	0.0090	0.0106
16	0.0082	0.0097	0.0115
17	0.0078	0.0094	0.0113
18	0.0080	0.0097	0.0119
19	0.0071	0.0088	0.0111
20	0.0072	0.0093	0.0121
21	0.0055	0.0075	0.0101
22	0.0066	0.0095	0.0137
23	0.0067	0.0107	0.0170
24	0.0065	0.0140	0.0201
25	0.0062	0.0115	0.0213
26	0.0090	0.0199	0.0444
27	0.0025	0.0077	0.0239
28	0.0009	0.0067	0.0473

Table 3.13: Exponential Parameter Estimation for Wheel Assembly Subsystem

Failure Number	Lower 95% C.I.	Estimated λ	Upper 95% C.I.
2	0.0025	0.0029	0.0033
3	0.0029	0.0033	0.0038
4	0.0026	0.0030	0.0035
5	0.0028	0.0032	0.0038
6	0.0030	0.0035	0.0041
7	0.0034	0.0041	0.0049
8	0.0029	0.0035	0.0044
9	0.0029	0.0038	0.0049
10	0.0037	0.0051	0.0069
11	0.0049	0.0070	0.0101
12	0.0031	0.0049	0.0077
13	0.0019	0.0039	0.0082
14	0.0032	0.0086	0.0229
15	0.0068	0.0211	0.0655
16	0.0011	0.0076	0.0542

For all the subsystems, many of the confidence intervals on λ overlap. This implies that these values of λ may be the same. Thus, we attempted to combine consecutive failure numbers into a single probability distribution model. In order to appropriately combine the different failure numbers, a homogeneity test needed to be performed. The purpose of a homogeneity test is to determine if different random variables have the same probability distribution. We could not find an appropriate homogeneity test that could handle the censored time between failure values. Thus, all the censored observations were removed before performing the homogeneity test. We then used χ^2 contingency tests (Montgomery and Runger, 1999) to determine which failure numbers could be combined into a single probability distribution.

To demonstrate the contingency testing process, we use the engine subsystem. First, we tested combining the 2nd and 3rd failure numbers. For this test, our null and alternative hypotheses are

H_0: T_2 and T_3 are homogeneous

H_1: T_2 and T_3 are not homogeneous

where T_2 denotes the time between the 1st and 2nd failure, and T_3 denotes the time between the 2nd and 3rd failure. To test these hypotheses, we first constructed the χ^2 contingency tables (Tables 3.14 and 3.15), where O_{ij} denotes the observed frequency for time interval i and failure number j and E_{ij} denotes the expected frequency for time interval i and failure number j.

Table 3.14: Observed Frequencies

i	Time Interval	j		Totals
		1	2	
		2nd Failure	3rd Failure	
1	(0,100]	42	26	68
2	(100,200]	25	29	54
3	(200,300]	25	29	54
4	(300,400]	12	26	38
5	(400,500]	22	12	34
6	(500,600]	16	18	34
7	(600,700]	13	12	25
8	(700,800]	9	8	17
9	(800,900]	9	10	19
10	(900,1000]	6	4	10
11	(1000,∞]	12	3	15
	Totals	191	177	368

Table 3.15: Expected Frequencies

i	Time Interval	j		$\hat{u}_i$
		1	2	
		2nd Failure	3rd Failure	
1	(0,100]	35	33	0.1848
2	(100,200]	28	26	0.1467
3	(200,300]	28	26	0.1467
4	(300,400]	20	18	0.1033
5	(400,500]	18	16	0.0924
6	(500,600]	18	16	0.0924
7	(600,700]	13	12	0.0679
8	(700,800]	9	8	0.0462
9	(800,900]	10	9	0.0516
10	(900,1000]	5	5	0.0272
11	(1000,∞]	8	7	0.0408
	$\hat{v}_j$	0.5190	0.4810	

In order to compute E_{ij}, we need to estimate u_i and v_j, where u_i is the probability that a randomly selected elements falls in time interval i and v_j is the probability that a randomly selected element falls in failure number j. Thus, the estimators of u_i and v_i are

$$\hat{u}_i = \frac{1}{n}\sum_{j=1}^{2} O_{ij} \tag{3.1}$$

$$\hat{v}_j = \frac{1}{n}\sum_{i=1}^{11} O_{ij} \tag{3.2}$$

where n is the total number of failures. Therefore, the expected frequency of each cell is

$$E_{ij} = n\hat{u}_i\hat{v}_j \tag{3.3}$$

The next step in the contingency testing process is to compute the test statistic

$$\chi_0^{\ 2} = \sum_{i=1}^{11}\sum_{j=1}^{2}\frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}} = 18.02 \tag{3.4}$$

We reject the null hypothesis if the test statistic is greater than the critical value

$$\chi^2_{0.05,10} = 18.31$$

Note that the 0.05 indicates the level of significance, and 10 denote the degrees of freedom for the test. Since, $\chi_0^{\ 2} < 18.31$ we fail to reject the null hypothesis and conclude that the 2nd and 3rd failure numbers are homogeneous.

Next, we attempted to combine the 2nd, 3rd, and 4th failures using the same procedure. Tables 3.16 and 3.17 show the contingency tables for this test.

Table 3.16: Observed Frequencies

i	Time Interval	j			Totals
		1	2	3	
		2nd Failure	3rd Failure	4th Failure	
1	(0,100]	42	26	41	109
2	(100,200]	25	29	33	87
3	(200,300]	25	29	19	73
4	(300,400]	12	26	21	59
5	(400,500]	22	12	14	48
6	(500,600]	16	18	10	44
7	(600,700]	13	12	3	28
8	(700,800]	9	8	5	22
9	(800,900]	9	10	2	21
10	(900,1000]	6	4	1	11
11	(1000,∞]	12	3	2	17
	Totals	191	177	151	519

Table 3.17: Expected Frequencies

i	Time Interval	j			$\widehat{u}_i$
		1	2	3	
		2^{nd} Failure	3^{rd} Failure	4^{th} Failure	
1	(0,100]	40	37	32	0.2100
2	(100,200]	32	30	25	0.1676
3	(200,300]	27	25	21	0.1407
4	(300,400]	22	20	17	0.1137
5	(400,500]	18	16	14	0.0925
6	(500,600]	16	15	13	0.0848
7	(600,700]	10	10	8	0.0539
8	(700,800]	8	8	6	0.0424
9	(800,900]	8	7	6	0.0405
10	(900,1000]	4	4	3	0.0212
11	(1000,∞]	6	6	5	0.0328
	$\widehat{v}_j$	0.3680	0.3410	0.2909	

The value of the test statistic is $\chi_0^2 = 41.43$ and the critical value is $\chi^2_{0.05,20} = 31.41$. Thus, we reject the null hypothesis and conclude that the 2nd, 3rd, and 4th failure numbers are not homogeneous.

The third attempt was to combine the 4th and 5th failure numbers, and the results show that 4th and 5th failure numbers are homogeneous. The fourth attempt was to combine the 4th, 5th, and 6th failure numbers. However, the result shows that the 4th, 5th, and 6th failure numbers are not homogeneous. The fifth attempt was to combine the 6th ,7th, and 8th failure numbers. The result shows that the 6th, 7th, and 8th failure numbers are homogeneous. The six attempt was to combine the 4th - 8th failure numbers. The result shows that those failure numbers are homogeneous. Finally, we attempted to combine the 2nd – 8th failure numbers. The result shows that 2nd – 8th failure numbers are not homogeneous. Thus, we concluded that 2nd to 3rd failure numbers could be combined and all failure numbers greater than or equal to 4 could be combined. Table 3.18 shows the combined failure numbers for the five subsystems.

Table 3.18: Combined Failure Numbers

Subsystem	Combined Failure Numbers
Refrigeration	$2^{nd} - 4^{th}$
	5^{th} +
Engine	$2^{nd} - 3^{rd}$
	4^{th} +
Tire	$2^{nd} - 6^{th}$
	7^{th} +
Wheel Assembly	$2^{nd} - 8^{th}$
	9^{th} +
Structure	1^{st} +

After confirming the consecutive failure numbers that can be combined into a single probability distribution, Weibull ++ software was used to fit a Weibull distribution and an exponential distributions to each set of combined failures for each subsystem. In addition, 95% confidence intervals on the Weibull shape parameter (β) were used to evaluate the corresponding hazard functions. Tables 3.19 - 3.23 show the results for the five subsystems.

Table: 3.19: Combined Failure Estimation for Refrigeration Subsystem

Failure Number	Weibull				Exponential		
	Lower 95% C.I.	$\hat{\beta}$	Upper 95% C.I.	$\hat{\eta}$	Lower 95% C.I.	$\hat{\lambda}$	Upper 95% C.I.
$2^{nd} - 4^{th}$	0.7453	0.8273	0.9182	1000.00	0.0009	0.0010	0.0012
5^{th} +	0.8601	1.1106	1.4312	500.00	0.0015	0.0020	0.0027

Table: 3.20: Combined Failure Estimation for Engine Subsystem

Failure Number	Weibull				Exponential		
	Lower 95% C.I.	$\hat{\beta}$	Upper 95% C.I.	$\hat{\eta}$	Lower 95% C.I.	$\hat{\lambda}$	Upper 95% C.I.
$2^{nd} - 3^{rd}$	1.0026	1.0900	1.1849	442.87	0.0021	0.0023	0.0026
4^{th} +	0.8337	0.9013	0.9743	344.83	0.0026	0.0029	0.0032

Table: 3.21: Combined Failure Estimation for Tire Subsystem

Failure Number	Weibull				Exponential		
	Lower 95% C.I.	$\hat{\beta}$	Upper 95% C.I.	$\hat{\eta}$	Lower 95% C.I.	$\hat{\lambda}$	Upper 95% C.I.
$2^{nd} - 6^{th}$	1.0335	1.0860	1.1411	170.16	0.0057	0.0061	0.0065
7^{th} +	0.9895	1.0225	1.0566	106.38	0.0090	0.0094	0.0098

Table: 3.22: Combined Failure Estimation for Wheel Assembly Subsystem

Failure Number	Weibull				Exponential		
	Lower 95% C.I.	$\hat{\beta}$	Upper 95% C.I.	$\hat{\eta}$	Lower 95% C.I.	$\hat{\lambda}$	Upper 95% C.I.
$2^{nd} - 8^{th}$	1.0849	1.1360	1.1896	320.37	0.0031	0.0032	0.0034
9^{th} +	0.9487	1.0838	1.2380	217.39	0.0040	0.0046	0.0054

Table: 3.23: Combined Failure Estimation for Structure Subsystem

Failure Number	Weibull				Exponential		
	Lower 95% C.I.	$\hat{\beta}$	Upper 95% C.I.	$\hat{\eta}$	Lower 95% C.I.	$\hat{\lambda}$	Upper 95% C.I.
1^{st} +	0.9044	1.0254	1.1626	2500.00	0.0003	0.0004	0.0004

The individual subsystem models were determined by analyzing Tables 3.19 - 3.23. If 1.0 is contained in the confidence interval on β, then the exponential distribution was selected; otherwise, the Weibull distribution was selected. Table 3.24 shows all the individual subsystem models.

Table 3.24: Individual Subsystem Models

Refrigeration Subsystem

Failure Number	Distribution	Estimated β	Estimated η	Estimated λ
1^{st}	Weibull	1.3594	1385.11	
$2^{nd} - 4^{th}$	Exponential			0.0010
5^{th} +	Exponential			0.0020

Engine Subsystem

Failure Number	Distribution	Estimated β	Estimated η	Estimated λ
1^{st}	Weibull	1.8282	696.07	
$2^{nd} - 3^{rd}$	Weibull	1.0900	442.87	
4^{th} +	Exponential			0.0029

Tire Subsystem

Failure Number	Distribution	Estimated β	Estimated η	Estimated λ
1^{st}	Weibull	2.0300	494.59	
$2^{nd} - 6^{th}$	Weibull	1.0860	170.16	
7^{th} +	Exponential			0.0094

Wheel Assembly Subsystem

Failure Number	Distribution	Estimated β	Estimated η	Estimated λ
1^{st}	Weibull	2.1492	635.11	
$2^{nd} - 8^{th}$	Weibull	1.1360	320.37	
9^{th} +	Exponential			0.0046

Structure Subsystem

Failure Number	Distribution	Estimated β	Estimated η	Estimated λ
1^{st}+	Exponential			0.0004

3.3 Retirement Policy and Trailer Duty Evaluation

The main objective of the applied portion of this research was to evaluate Tyson's trailer retirement policy and trailer duty assignments. In order to evaluate Tyson's policies, the probability models developed in the previous sections were used in conjunction with a discrete-event simulation model of trailer performance.

The simulation model, constructed in Microsoft Visual Basic, mimics the failure of the five subsystems (the code for the simulation model can be found in section B.1 of Appendix B). The performance measures captured by the simulation output include the number of failures and the maintenance costs for each subsystem. Based on part costs and repair times provided by Tyson personnel, the triangular probability distribution was used to model the maintenance costs associated with an individual subsystem failure. Table 3.25 shows the minimum, mode, and maximum maintenance costs for each type of subsystem failure. These values were chosen through discussion with Tyson's maintenance personnel. The maintenance costs shown in Table 3.25 include parts, labor ($22/hour), and outside repair (on the road) costs. However, in this research, the outside repair costs were assumed to be the same as inside repair. The simulation model was verified through use of Microsoft Visual Basic debugging (tracing) tools to see if the code correctly captured the failure of the trailers.

Table 3.25: Maintenance Costs for Each Subsystem Failure

Subsystem	Minimum	Mode	Maximum
Refrigeration	$25	$460	$2,176
Engine	$25	$119	$3,130
Tire	$13	$93	$337
Wheel Assembly	$22	$240	$2,420
Structure	$22	$933	$21,080

The simulation model was executed using a run length of 12 years and 100,000 replications. Tables 3.26 and 3.27 show the simulation output. The model output was validated via Tyson's historical data on the average number of failures for each subsystem over 7 years and the average trailer maintenance costs in year 7. Tables 3.28 and 3.29 show the comparison between the Tyson's historical data and the simulation output. In the Tyson's historical data, only failures or non-preventive maintenance activities were considered. In addition, only labor, parts, tires, and outside repair (on the road) costs were included in the average maintenance costs.

Table 3.26: Applied Problem Simulation Output – Average Number of Failures

Year	Subsystems					Total
	Refrigeration	Engine	Tire	Wheel Assembly	Structure	
1	0.18	0.20	0.73	0.35	0.14	1.60
2	0.46	0.73	2.74	1.39	0.29	5.61
3	0.79	1.51	5.23	2.63	0.44	10.60
4	1.16	2.42	8.15	3.84	0.59	16.16
5	1.55	3.40	11.39	5.07	0.74	22.15
6	1.96	4.41	14.76	6.37	0.88	28.38
7	2.39	5.44	18.18	7.75	1.03	34.79
8	2.84	6.49	21.60	9.23	1.17	41.33
9	3.33	7.54	25.03	10.79	1.32	48.01
10	3.84	8.60	28.46	12.40	1.46	54.76
11	4.37	9.66	31.88	14.05	1.61	61.57
12	4.94	10.72	35.31	15.72	1.76	68.45

Table 3.27: Applied Problem Simulation Output – Average Maintenance Costs

Year	Subsystems					Total
	Refrigeration	Engine	Tire	Wheel Assembly	Structure	
1	$155	$213	$109	$314	$1,058	$1,849
2	$405	$795	$405	$1,245	$2,145	$4,995
3	$702	$1,643	$773	$2,352	$3,231	$8,701
4	$1,028	$2,633	$1,204	$3,433	$4,331	$12,629
5	$1,374	$3,699	$1,682	$4,535	$5,418	$16,708
6	$1,736	$4,800	$2,179	$5,692	$6,485	$20,892
7	$2,121	$5,928	$2,684	$6,927	$7,544	$25,204
8	$2,523	$7,071	$3,190	$8,248	$8,631	$29,663
9	$2,953	$8,217	$3,697	$9,643	$9,709	$34,219
10	$3,406	$9,368	$4,204	$11,083	$10,764	$38,825
11	$3,883	$10,528	$4,708	$12,557	$11,855	$43,531
12	$4,378	$11,682	$5,215	$14,044	$12,944	$48,263

Table 3.28: Simulation Model Validation - Average Number of Failures

Subsystem	Refrigeration	Engine	Tire	Wheel Assembly	Structure
Simulation Output	2.39	5.44	18.18	7.76	1.02
Tyson's Data	2.31	5.14	17.71	7.40	0.94

Table 3.29: Simulation Model Validation - Average 7th year Maintenance Costs

	Average 7th Year Maintenance Costs
Simulation Output	$4,312.08
Tyson's Data	$4,414.57

The results indicate that the simulation model provides accurate measures of system performance. For the average year 7 trailer maintenance cost, it was expected that Tyson's data would be slightly higher than simulation output. Since, the outside repair costs are higher than the inside repair, and in the simulation model, the outside repair costs were assumed to be the same as inside repair.

Currently, Tyson's trailer retirement policy is to retire a trailer after 7 years of service. In this research, cost analysis was used to evaluate this policy. The analysis was based on total maintenance costs, salvage value, and purchase costs for a trailer. The salvage value and the purchase price were collected from Tyson's transportation department, and the total maintenance costs were collected from the simulation output. The total maintenance costs included the maintenance costs for each subsystem. The total annual cost for a trailer (TAC_j) retired after j years is

$$TAC_j = \frac{(P + TC_j - SV_j)}{j} \tag{3.5}$$

Where P denotes the price for a new refrigerated trailer, TC_j denotes the estimated total maintenance costs if the trailer is used for j years, and SV_j denotes the salvage value after year j.

The total annual cost is minimized if the trailer is retired after 7 years of service. Retirement policies beyond 8 years were not considered in this analysis because the probability distribution used to model trailer reliability was based on a 7-year data collection period.

Another important issue in the refrigerated trailer transportation system is to determine trailer duty or assignment. The assignment can include all duties within the natural progression of long haul use, local shuttle use, and facility refrigerated storage. The output of the simulation model can be used as a guideline for the fleet manager to determine which trailers could be considered as relatively better than others having fewer mechanical failures and reduced maintenance costs. In turn, this information can be used in trailer assignment decisions.

The previous simulation model had to be modified in order to perform the trailer duty analysis. The performance measures in previous simulation model were the average number of failures and the average maintenance costs for each subsystem. In the modified simulation model (code B.2 in Appendix B), the performance measures are the total number of failures and the total maintenance costs for each trailer. With the simulation model, failure and cost data were generated for 1000 trailers over 7 years. Example simulation results for 15 trailers can be found in Tables 3.30 and 3.31.

Table 3.30: Example Simulation Results – Total Number of Failures

Trailer	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
1	0	4	9	16	27	32	37
2	1	2	9	15	25	28	34
3	1	8	13	14	19	24	28
4	0	6	14	15	20	27	38
5	4	7	14	25	36	44	48
6	0	6	11	15	21	27	31
7	2	5	12	16	24	34	40
8	0	7	13	21	24	28	32
9	2	10	17	25	30	39	44
10	2	5	9	11	18	28	38
11	0	1	11	23	26	32	37
12	2	4	12	16	19	24	31
13	1	4	7	12	16	25	34
14	0	1	5	8	12	13	15
15	2	9	13	18	27	34	38

Table 3.31: Example Simulation Results - Total Maintenance Costs

Trailer	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
1	$0	$2,587	$5,154	$7,024	$16,520	$19,524	$20,851
2	$1,061	$1,287	$10,207	$15,991	$21,108	$22,578	$23,525
3	$236	$3,364	$15,863	$15,968	$20,330	$21,961	$24,943
4	$0	$6,727	$11,370	$12,413	$15,725	$19,563	$25,213
5	$4,570	$5,078	$8,045	$13,350	$24,931	$26,761	$27,545
6	$0	$805	$2,765	$25,729	$30,644	$33,537	$40,827
7	$1,762	$2,200	$6,024	$9,446	$13,525	$26,575	$30,159
8	$0	$3,069	$4,220	$6,688	$8,335	$10,416	$10,903
9	$1,966	$5,455	$9,780	$12,940	$14,880	$18,089	$26,458
10	$357	$1,596	$3,522	$4,159	$5,660	$10,782	$14,180
11	$0	$1,843	$6,079	$11,402	$27,245	$29,709	$30,975
12	$3,007	$4,588	$10,262	$13,311	$14,360	$25,799	$29,906
13	$15,770	$17,481	$19,619	$22,490	$34,138	$37,657	$41,140
14	$0	$48	$718	$3,907	$5,365	$5,963	$7,879
15	$190	$7,116	$7,744	$9,397	$13,508	$18,514	$21,115

In order to determine the trailer duty guideline, Tables 3.32 and 3.33 were created using the simulated data on all 1000 trailers. First, the total number of failures and the total maintenance costs were sorted for each year. Next, percentiles on the number of failures and the total maintenance costs for each year were computed.

Table 3.32: Expected Life-to-Date Total Number of Failures for Given Percentile

Year	Percentile								
	1%	5%	10%	25%	50%	75%	90%	95%	99%
1	0	0	0	0	1	2	3	4	6
2	1	2	2	4	5	7	9	10	13
3	4	5	6	8	10	13	16	17	20
4	7	9	10	13	16	19	22	24	28
5	10	14	15	18	22	26	29	31	36
6	15	19	21	24	28	33	36	39	43
7	20	25	27	30	34	39	43	46	49

Table 3.33: Expected Life-to-Date Total Maintenance Costs ($) for Given Percentile

Year	Percentile								
	1%	5%	10%	25%	50%	75%	90%	95%	99%
1	$0	$0	$0	$0	$528	$1,881	$5,506	$9,883	$16,535
2	$37	$420	$768	$1,728	$3,339	$6,614	$11,937	$15,855	$24,066
3	$888	$1,961	$2,692	$4,224	$6,783	$11,540	$17,820	$22,081	$30,277
4	$2,477	$3,725	$5,118	$7,153	$10,642	$16,422	$23,829	$27,974	$35,561
5	$4,339	$6,407	$7,807	$10,658	$14,794	$20,856	$29,176	$33,886	$41,649
6	$6,779	$9,013	$10,415	$13,968	$18,941	$26,025	$33,708	$38,550	$47,827
7	$9,110	$11,666	$14,053	$17,466	$23,262	$30,733	$39,152	$44,207	$54,416

Tables 3.32 and 3.33 are potentially very useful by providing a quantitative means to evaluate trailer performance. The left side of the tables corresponds to trailers with better historical performance as compared to middle and higher percentiles. The data contained within them allow the user to evaluate past degradation (failures) and history (failures and cost) relative to desired criteria (percentile). The percentile tables can be used in three foreseen ways:

- to compare same-age trailers in an effort to identify trailers with relatively few failures and/or low life-to-date costs,
- to compare same age trailers in an effort to identify trailers with relatively many failures and/or high life-to-date costs, and
- to track the reliability performance of trailers of different ages.

As a simple example, if a fifth year trailer has 14 total failures (5^{th} percentile) and $8,000 total maintenance costs (10^{th} percentile), the trailer can be considered as better than a fifth year trailer with 30 failures (90 - 95^{th} percentile) and $34,000 total maintenance costs (95^{th} percentile). In this case, the company may choice to use the first trailer in different ways than the second. When it is time to sell trailers from a given fleet year, then those in the lowest percentile may be kept for local use (i.e., shuttle and storage). Using the raw data, we also computed the actual number of trailers in each percentile. Table 3.34 shows these results.

Table 3.34: Actual Number of Trailers for Given Percentile (Raw Data)

<table>
<tr><th rowspan="2">Year</th><th colspan="9">Percentile</th></tr>
<tr><th>1%</th><th>5%</th><th>10%</th><th>25%</th><th>50%</th><th>75%</th><th>90%</th><th>95%</th><th>99%</th></tr>
<tr><td>1</td><td colspan="4">78</td><td>56</td><td>35</td><td>17</td><td>7</td><td>2</td></tr>
<tr><td>2</td><td>13</td><td colspan="2">29</td><td>19</td><td>53</td><td>47</td><td>12</td><td>16</td><td>6</td></tr>
<tr><td>3</td><td>8</td><td>5</td><td>25</td><td>37</td><td>40</td><td>33</td><td>24</td><td>15</td><td>8</td></tr>
<tr><td>4</td><td>6</td><td>6</td><td>11</td><td>36</td><td>42</td><td>35</td><td>26</td><td>18</td><td>15</td></tr>
<tr><td>5</td><td>5</td><td>4</td><td>12</td><td>25</td><td>46</td><td>42</td><td>25</td><td>18</td><td>18</td></tr>
<tr><td>6</td><td>1</td><td>10</td><td>8</td><td>24</td><td>41</td><td>45</td><td>18</td><td>20</td><td>28</td></tr>
<tr><td>7</td><td>7</td><td>11</td><td>9</td><td>21</td><td>33</td><td>41</td><td>30</td><td>21</td><td>22</td></tr>
</table>

4. FUTURE DIRECTIONS

The analysis presented in this research is limited in two ways. First, the probability models are based entirely on a 7-year data collection period. Extrapolating these models beyond a 7-year period is not recommended. Second, the cost parameters used in the retirement and duty analyses are not duty-specific. In other words, the cost parameters for given subsystems are the same regardless of trailer duty at the time of failure.

Therefore, we recommend two directions for future study. First, we recommend using probability models of trailer reliability and maintainability that can be extrapolated beyond a 7-year period. For example, we recommend using models based on minimal repair and imperfect repair practices. Second, we recommend conducting the retirement and duty analyses with repair cost parameters that depend on trailer duty at the time of failure.

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Appendix A

Tyson Fleet Maintenance Information

Figure A.1: Tyson's PM Worksheet

TYSON FOODS, INC.
Service Center Division
PM INSPECTION & WORK SHEET

Division________________________ Date ____________ Vehicle No. ____________________

Year, Make, Model _________________________________ Odometer Reading _________________

I. IN CAB

1. Brakes Service [ ]
2. Brake Parking [ ]
3. Clutch [ ]
4. Windshield Wipers [ ]
5. All Gauges & Instrument [ ]
6. Horn [ ]
7. Lights & Turn Signal [ ]
8. Glass [ ]
9. Rear View Mirror [ ]
10. Fire Extinguisher [ ]
11. Reflector Kit and /or Fuses [ ]
12. Steering [ ]
13. State Inspection/DOT[ ]

13a. Seat Belt [ ]

II. UNDER HOOD

14. Radiator, Hoses & Shutters [ ]
15. Antifreeze [ ]
16. Intake Manifold Heat Control Valve [ ]
17. Fan Belts [ ]
18. Governor & Cables [ ]
19. Battery & Cables [ ]
20. PCV Valve & Breathers [ ]

III. UNDER TRUCK

21. Exhaust System [ ]
22. Springs, Shackles, U Bolts, Pads, Cushions & Hangers [ ]
23. U Joints, Prop. Shaft, Center Brg. [ ]
24. Steering Connections & Shock Absorbers [ ]
25. Air Tanks Drain [ ]
26. Brake Lines & Cables [ ]
27. Leaks, Oil, Grease, etc. [ ]
28. Mounts, Body, 5th Wheel, Engine, Trans. [ ]

IV. OUTSIDE TRUCK

29. Tire Chains [ ]
30. Reflectors [ ]
31. Wheels & Lug Bolts, Axle, Flange Nuts [ ]
32. Tires [ ]
33. Body & Hardware [ ]

V. SPECIAL EQUIPMENT

34. Chairs & Sprocket Drive [ ]
35. Hydraulic Pumps, Motor Hose, Tank, etc. [ ]

VI. LUBRICATE ACCORDING TO SPEC. DRAIN & FILL

36. Engine Crankcase [ ]
37. Transmission [ ]
38. Differential [ ]
39. Oil Filter [ ]
40. Water Filter [ ]
41. Fuel Filter [ ]
42. Trans. Filter [ ]
43. Air Filter [ ]

REMARKS ________________________

____

[√] INDICATES ITEM SERVICEABLE
[X] INDICATES CORRECTIVE ACTION NEEDED

CIRCLE "X" WHEN CORRECTIVE ACTION IS TAKEN

SIGNATURE OF INSPECTOR _________________

Table A.1: Subsystem Failure Types

Refrigeration		Engine	
PM	Failure	PM	Failure
Drier	3-Way-Valve By-Pass Check Valve Compressor Seal Compressor Condenser Discharge Vibrasorber Defrost Switch Evaporator Fan Expansion Valve Hose Vibrasorber Hot Gas Tube Pilot Solenoid Rebuild Compressor Accumulator Tank Repair Freon Line Suction Vibrasorber Thermal Switch Throttling Valve	Air Filter Air Leaks Alternator Belt Ammeter Battery Engine Seal Fan Belt Fan Drive Belt Fueled Unit Gear Kit Oil Level Switch Oil Seal Starter Water Pump Water Pump Gauge	Alternator Battery Battery Lead Post Bushing Cam shaft Click On Switch Coupling Cycle Central Module Engine Seal Exhaust Tube Exhaust Stud Fuel Leaks Fan Shaft Fuel Filter Fuel Line Fuel Solenoid Fuel Tank Fueled Unit Gear Kit Hour Meter HPCO Switch Idle Pulley Injector Injector Pump Motor Oil Level Switch Oil Sensor Pressure Switch Radiator Regulator Relay Valve Reset Switch RPM Sensor Thermostat Bolt Thermostat Timing Gear Water Pump Drive Belt Water Pump Water Pump Gauge

Table A.1: Subsystems Failure Types

Tire		Wheel Assembly	
PM	Failure	PM	Failure
Mount/Dismount Pull Off Tire Recap Tire Casing Tires	Cap Tire/Recap Flat Tire Mount/Dismount Patch Tire Pull Off Tire Replace Tire Stem Tires Tires Spares Valve Stem	Adjust Brakes Align Axles Axles Wheel Seals Brakes Brakes Axles Brakes Drums Brakes Shoes Replace Hub Cap Brakes Spring Wheel Seals	Adjust Brakes Axle Brakes Axles Bearings Brake Chamber Brake Valve Brakes Brakes Shoes/Lining Cam Shaft Drums Hub Oiler/Hub Cap Pilot Hole Wheel/Rim Repair Suspension S-Cam Bushing Wheel Casing Wheel Seals
Electrical		**Structure**	
PM	Failure	PM	Failure
Panel Lights	Bulb Pig Tail Repair Lights	Door Roof	Air Chute Blow-Out Plate Bumper Door Hinges Door Wouldn't Shut Floor Repair Landing Gear Mud Flaps Nose Rail Paint Trailer Red Reflector Doors Vent Door Tandem Slide Tandem Slide Handle Wall Damage Wreck Damage

Table A.2: Time Between Failure Data for Refrigeration Subsystem

Appendix B

Visual Basic Simulation Code

Program B.1: Visual Basic Simulation Model Coding for Trailer Retirement Policy

```
Const MaxObs As Long = 12
Const Subsystems As Long = 5
Const NumReps As Long = 100

Dim J As Long
Dim I As Long
Dim Tnow As Double
Dim NextFailure As Double
Dim NextObs As Double
Dim FailedSubsystem As Long
Dim NextFailureTime(Subsystems) As Double
Dim NextFailureNumber(Subsystems) As Long
Dim NumberOfFailures(Subsystems) As Long
Dim Cost(Subsystems) As Double
Dim Obs As Long
Dim Tend As Double
Dim Running As Boolean

Dim oExcel As Object
Dim oBook As Object
Dim oSheet As Object

Dim TotalNumberOfFailures(Subsystems, MaxObs) As Long
Dim TotalNumberOfFailuresSqr(Subsystems, MaxObs) As Double
Dim AvgNumberOfFailures(Subsystems, MaxObs) As Double
Dim StdDevNumberOfFailures(Subsystems, MaxObs) As Double
Dim TotalCost(Subsystems, MaxObs) As Double
Dim TotalCostSqr(Subsystems, MaxObs) As Double
Dim AvgCost(Subsystems, MaxObs) As Double
Dim StdDevCost(Subsystems, MaxObs) As Double

************************************************************************

Private Sub Command1_Click()

Call Randdf

'Start Excel and get Application object

Set oExcel = CreateObject("Excel.Application")
oExcel.Visible = True


'Get a new workbooks

Set oBook = oExcel.Workbooks.Add
Set oSheet = oBook.Worksheets(1)

oSheet.Range("D1:K1").Value = Array("MaxObs", "NumReps", "T.Subsys.",
"Refrig.", "Engine", _"Tire", "W.Assem.", "Struct.")


oSheet.Range("G2:K2").Value = Array("1", "2", "3", "4", "5")
```

```
oSheet.Range("D2:F2").Value = Array(MaxObs, NumReps, Subsystems)

oSheet.Range("A1").Value = Array("Applied_Problem_1")


For I = 1 To Subsystems

    For J = 1 To MaxObs

    TotalNumberOfFailures(I, J) = 0
    TotalNumberOfFailuresSqr(I, J) = 0

    TotalCost(I, J) = 0#
    TotalCostSqr(I, J) = 0#

    Next J

Next I


For J = 1 To NumReps

Call Initialization

'Event processor
'Set minimum time for Failure, Replace, and Repair

Do While Running

    NextFailure = Tend + 1#
    FailedSubystem = Subsystems + 1
    For I = 1 To Subsystems
        If NextFailureTime(I) < NextFailure Then
            NextFailure = NextFailureTime(I)
            FailedSubsystem = I
        End If

 Next I


'Determine the minimum time within NextFailure and NextObs
'and call the event with minimum time

    If NextFailure <= NextObs Then
        Call Failure

    Else
        Call Observation

    End If
Loop
Next J
```

```
'Make Excel visible and give the user control
'of Microsoft Excel

oExcel.Visible = True
oExcel.UserControl = True
oSheet.application.Visible = True
oSheet.Parent.windows(1).Visible = True

For I = 1 To Subsystems

    For J = 1 To MaxObs

    AvgNumberOfFailures(I, J) = TotalNumberOfFailures(I, J) / NumReps
    StdDevNumberOfFailures(I, J) = Sqr((TotalNumberOfFailuresSqr(I, J)-
    _((TotalNumberOfFailures(I, J) ^ 2 / NumReps))) / (NumReps - 1))

    oSheet.cells(5, 3).Value = "Average - Number Of Failures"
    oSheet.cells(22, 3).Value = "Standard Deviation - Number Of
                                 Failures"
    oSheet.cells(6, 1).Value = "    Obs."

    oSheet.cells(6 + J, 1) = J
    oSheet.cells(6, 2 + I) = I
    oSheet.cells(6, 8 + I) = I
    oSheet.cells(6 + J, 2 + I) = AvgNumberOfFailures(I, J)
    oSheet.cells(23 + J, 2 + I) = StdDevNumberOfFailures(I, J)

    AvgCost(I, J) = TotalCost(I, J) / NumReps
    StdDevCost(I, J) = Sqr((TotalCostSqr(I, J) - _
                       ((TotalCost(I, J) ^ 2/NumReps)))/(NumReps - 1))

    oSheet.cells(5, 9).Value = "Average - Cost"
    oSheet.cells(22, 9).Value = "Standard Deviation - Cost"
    oSheet.cells(23, 1).Value = "    Obs."

    oSheet.cells(23 + J, 1) = J
    oSheet.cells(23, 2 + I) = I
    oSheet.cells(23, 8 + I) = I
    oSheet.cells(6 + J, 8 + I) = AvgCost(I, J)
    oSheet.cells(23 + J, 8 + I) = StdDevCost(I, J)

    Next J

Next I

'Save the workbook
oBook.SaveAs "C:\Applied_Problem_Output.xls"

'Release object references
Set oExcel = Nothing
Set oBook = Nothing
Set oSheet = Nothing

End
End Sub

**********************************************************************
```

```
Public Sub Initialization()

'Initialization state

Tnow = 0#
Tend = MaxObs * 365
NextObs = 365#
Obs = 1

For I = 1 To Subsystems
    Cost(I) = 0#
    NumberOfFailures(I) = 0
    NextFailureNumber(I) = 1
Next I

    NextFailureTime(1) = Weibull(1.3594, 1385.11, 1)
    NextFailureTime(2) = Weibull(1.8282, 969.07, 1)
    NextFailureTime(3) = Weibull(2.03, 494.59, 1)
    NextFailureTime(4) = Weibull(2.1492, 635.11, 1)
    NextFailureTime(5) = Exponential(0.0004, 1)

Running = True

End Sub

**********************************************************************


Public Sub Failure()

'Failure event

Tnow = NextFailure
Select Case FailedSubsystem

Case 1

    NumberOfFailures(1) = NumberOfFailures(1) + 1
    Cost(1) = Cost(1) + Triangular(10, 20, 100, 1)
    NextFailureNumber(1) = NextFailureNumber(1) + 1

    If (NextFailureNumber(1) >= 2) And (NextFailureNumber(1) <= 4) Then
        NextFailureTime(1) = Tnow + Exponential(0.001, 1)
    Else
        NextFailureTime(1) = Tnow + Exponential(0.002, 1)
    End If

Case 2

    NumberOfFailures(2) = NumberOfFailures(2) + 1
    Cost(2) = Cost(2) + Triangular(10, 20, 100, 1)
    NextFailureNumber(2) = NextFailureNumber(2) + 1

    If (NextFailureNumber(2) >= 2) And (NextFailureNumber(2) <= 3) Then
        NextFailureTime(2) = Tnow + Weibull(1.09, 442.87, 1)
    Else
```

```
        NextFailureTime(2) = Tnow + Exponential(0.0029, 1)
    End If

Case 3

    NumberOfFailures(3) = NumberOfFailures(3) + 1
    Cost(3) = Cost(3) + Triangular(10, 20, 100, 1)
    NextFailureNumber(3) = NextFailureNumber(3) + 1

    If (NextFailureNumber(3) >= 2) And (NextFailureNumber(3) <= 6) Then
        NextFailureTime(3) = Tnow + Weibull(1.086, 170.16, 1)
    Else
        NextFailureTime(3) = Tnow + Exponential(0.0094, 1)
    End If

Case 4

    NumberOfFailures(4) = NumberOfFailures(4) + 1
    Cost(4) = Cost(4) + Triangular(10, 20, 100, 1)
    NextFailureNumber(4) = NextFailureNumber(4) + 1

    If (NextFailureNumber(4) >= 2) And (NextFailureNumber(4) <= 8) Then
        NextFailureTime(4) = Tnow + Weibull(1.136, 320.37, 1)
    Else
        NextFailureTime(4) = Tnow + Exponential(0.0046, 1)
    End If

Case 5

    NumberOfFailures(5) = NumberOfFailures(5) + 1
    Cost(5) = Cost(5) + Triangular(10, 20, 100, 1)
    NextFailureNumber(5) = NextFailureNumber(5) + 1

    NextFailureTime(5) = Tnow + Exponential(0.0004, 1)

End Select

End Sub

'************************************************************************


Public Sub Observation()

Tnow = NextObs

For I = 1 To Subsystems

    TotalNumberOfFailures(I, Obs) = TotalNumberOfFailures(I, Obs) +
      NumberOfFailures(I)
    TotalNumberOfFailuresSqr(I, Obs) = TotalNumberOfFailuresSqr(I, Obs)
      + 1# _*(NumberOfFailures(I) ^ 2)

    TotalCost(I, Obs) = TotalCost(I, Obs) + Cost(I)
    TotalCostSqr(I, Obs) = TotalCostSqr(I, Obs) + 1# * (Cost(I) ^ 2)
```

```
Next I

If Obs < 12 Then
    Obs = Obs + 1
    NextObs = NextObs + 365#
Else
    Running = False
End If

End Sub

'***********************************************************************
```

Program B.2: Visual Basic Modified Simulation Model Coding for Trailer Duty Analysis

```
Const MaxObs As Long = 7
Const Subsystems As Long = 5
Const NumReps As Long = 7

Dim J As Long
Dim I As Long
Dim Tnow As Double
Dim NextFailure As Double
Dim NextObs As Double
Dim FailedSubsystem As Long
Dim NextFailureTime(Subsystems) As Double
Dim NextFailureNumber(Subsystems) As Long
Dim NumberOfFailures(Subsystems) As Long
Dim Cost(Subsystems) As Double
Dim Obs As Long
Dim Tend As Double
Dim Running As Boolean

Dim oExcel As Object
Dim oBook As Object
Dim oSheet As Object

Dim TotalNumberOfFailures As Double
Dim UnitCost As Double
Dim TotalCost As Double


'************************************************************************



Private Sub Command1_Click()

Call Randdf

'Start Excel and get Application object

Set oExcel = CreateObject("Excel.Application")
oExcel.Visible = True

'Get a new workbooks

Set oBook = oExcel.Workbooks.Add
Set oSheet = oBook.Worksheets(1)


oSheet.Range("D1:K1").Value = Array("MaxObs", "NumReps", "T.Subsys.",
"Refrig.", "Engine", _"Tire", "W.Assem.", "Struct.")


oSheet.Range("G2:K2").Value = Array("1", "2", "3", "4", "5")
```

```
oSheet.Range("D2:F2").Value = Array(MaxObs, NumReps, Subsystems)

oSheet.Range("A1").Value = Array("Applied_Problem_2")
For J = 1 To NumReps


Call Initialization

'Event processor

'Set minimum time for Failure, Replace, and Repair

Do While Running

    NextFailure = Tend + 1#
    FailedSubystem = Subsystems + 1
    For I = 1 To Subsystems
        If NextFailureTime(I) < NextFailure Then
            NextFailure = NextFailureTime(I)
            FailedSubsystem = I
        End If
    Next I

'Determine the minimum time within NextFailure and NextObs
'and call the event with minimum time

    If NextFailure <= NextObs Then
        Call Failure

    Else
        Call Observation

    End If
Loop
Next J

'Make Excel visible and give the user control of Microsoft Excel

oExcel.Visible = True
oExcel.UserControl = True
oSheet.application.Visible = True
oSheet.Parent.windows(1).Visible = True

'Save the workbook
oBook.SaveAs "C:\Applied_Problem_Output2.xls"

'Release object references
Set oExcel = Nothing
Set oBook = Nothing
Set oSheet = Nothing

End

End Sub


'*********************************************************************
```

```
Public Sub Initialization()

'Initialization state

Tnow = 0#
Tend = MaxObs * 365
NextObs = 365#
Obs = 1

For I = 1 To Subsystems
    Cost(I) = 0#
    NumberOfFailures(I) = 0
    NextFailureNumber(I) = 1

Next I

    NextFailureTime(1) = Weibull(1.3594, 1385.11, 1) 'Refrigeration
subsystem
    NextFailureTime(2) = Weibull(1.8282, 969.07, 1)  'Engine subsystem
    NextFailureTime(3) = Weibull(2.03, 494.59, 1)    'Tire
    NextFailureTime(4) = Weibull(2.1492, 635.11, 1)  'Wheel assembly
    NextFailureTime(5) = Exponential(0.0004, 1)      'Structure

Running = True

End Sub

'**********************************************************************


Public Sub Failure()

'Failure event

Tnow = NextFailure
TotalNumberOfFailures = TotalNumberOfFailures + 1
Select Case FailedSubsystem

Case 1   'Refrigeration subsystem

    NumberOfFailures(1) = NumberOfFailures(1) + 1
    UnitCost = Triangular(25, 460, 2176, 1)
    Cost(1) = Cost(1) + UnitCost
    TotalCost = TotalCost + UnitCost
    NextFailureNumber(1) = NextFailureNumber(1) + 1

    If (NextFailureNumber(1) >= 2) And (NextFailureNumber(1) <= 4) Then
        NextFailureTime(1) = Tnow + Exponential(0.001, 1)
    Else
        NextFailureTime(1) = Tnow + Exponential(0.002, 1)
    End If

Case 2   'Engine subsystem

    NumberOfFailures(2) = NumberOfFailures(2) + 1
    UnitCost = Triangular(25, 119, 3130, 1)
```

```
        Cost(2) = Cost(2) + UnitCost
        TotalCost = TotalCost + UnitCost
        NextFailureNumber(2) = NextFailureNumber(2) + 1

        If (NextFailureNumber(2) >= 2) And (NextFailureNumber(2) <= 3) Then
            NextFailureTime(2) = Tnow + Weibull(1.09, 442.87, 1)
        Else
            NextFailureTime(2) = Tnow + Exponential(0.0029, 1)
        End If

    Case 3   'Tire Subsystem

        NumberOfFailures(3) = NumberOfFailures(3) + 1
        UnitCost = Triangular(13, 93, 337, 1)
        Cost(3) = Cost(3) + UnitCost
        TotalCost = TotalCost + UnitCost
        NextFailureNumber(3) = NextFailureNumber(3) + 1

        If (NextFailureNumber(3) >= 2) And (NextFailureNumber(3) <= 6) Then
            NextFailureTime(3) = Tnow + Weibull(1.086, 170.16, 1)
        Else
            NextFailureTime(3) = Tnow + Exponential(0.0094, 1)
        End If

    Case 4   'Wheel Assembly Subsystem

        NumberOfFailures(4) = NumberOfFailures(4) + 1
        UnitCost = Triangular(22, 240, 2420, 1)
        Cost(4) = Cost(4) + UnitCost
        TotalCost = TotalCost + UnitCost
        NextFailureNumber(4) = NextFailureNumber(4) + 1

        If (NextFailureNumber(4) >= 2) And (NextFailureNumber(4) <= 8) Then
            NextFailureTime(4) = Tnow + Weibull(1.136, 320.37, 1)
        Else
            NextFailureTime(4) = Tnow + Exponential(0.0046, 1)
        End If

    Case 5   'Structure Subsystem

        NumberOfFailures(5) = NumberOfFailures(5) + 1
        UnitCost = Triangular(22, 933, 21080, 1)
        Cost(5) = Cost(5) + UnitCost
        TotalCost = TotalCost + UnitCost
        NextFailureNumber(5) = NextFailureNumber(5) + 1

        NextFailureTime(5) = Tnow + Exponential(0.0004, 1)

    End Select

    End Sub

    '************************************************************************
```

```
Public Sub Observation()

Tnow = NextObs

oSheet.cells(6 + J, 2 + Obs) = TotalNumberOfFailures
oSheet.cells(20 + J, 2 + Obs) = TotalCost


If Obs < 7 Then
    Obs = Obs + 1
    NextObs = NextObs + 365#
Else
    Running = False
End If

End Sub

'***********************************************************************



Option Explicit


Public Zrng(1 To 100) As Long

'set the seeds for all 100 streams (Law and Kelton, 1991)

Public Sub Randdf()

Zrng(1) = 1973272912:  Zrng(2) = 281629770:   Zrng(3) = 20006270:
Zrng(4) = 1280689831:  Zrng(5) = 2096730329:  Zrng(6) = 1933576050:
Zrng(7) = 913566091:   Zrng(8) = 246780520:   Zrng(9) = 1363774876:
Zrng(10) = 604901985:  Zrng(11) = 1511192140: Zrng(12) = 1259851944:
Zrng(13) = 824064364:  Zrng(14) = 150493284:  Zrng(15) = 242708531:
Zrng(16) = 75253171:   Zrng(17) = 1964472944: Zrng(18) = 2102299975:
Zrng(19) = 233217322:  Zrng(20) = 1911216000: Zrng(21) = 726370533:
Zrng(22) = 403498145:  Zrng(23) = 993232223:  Zrng(24) = 1103205531:
Zrng(25) = 762430696:  Zrng(26) = 1922803170: Zrng(27) = 1385516923:
Zrng(28) = 76271663:   Zrng(29) = 413682397:  Zrng(30) = 726466604:
Zrng(31) = 336157058:  Zrng(32) = 1432650381: Zrng(33) = 1120463904:
Zrng(34) = 595778810:  Zrng(35) = 877722890:  Zrng(36) = 1046574445:
Zrng(37) = 68911991:   Zrng(38) = 2088367019: Zrng(39) = 748545416:
Zrng(40) = 622401386:  Zrng(41) = 2122378830: Zrng(42) = 640690903:
Zrng(43) = 1774806513: Zrng(44) = 2132545692: Zrng(45) = 2079249579:
Zrng(46) = 78130110:   Zrng(47) = 852776735:  Zrng(48) = 1187867272:
Zrng(49) = 1351423507: Zrng(50) = 1645973084: Zrng(51) = 1997049139:
Zrng(52) = 922510944:  Zrng(53) = 2045512870: Zrng(54) = 898585771:
Zrng(55) = 243649545:  Zrng(56) = 1004818771: Zrng(57) = 773686062:
Zrng(58) = 403188473:  Zrng(59) = 372279877:  Zrng(60) = 1901633463:
Zrng(61) = 498067494:  Zrng(62) = 2087759558: Zrng(63) = 493157915:
Zrng(64) = 597104727:  Zrng(65) = 1530940798: Zrng(66) = 1814496276:
Zrng(67) = 536444882:  Zrng(68) = 1663153658: Zrng(69) = 855503735:
Zrng(70) = 67784357:   Zrng(71) = 1432404475: Zrng(72) = 619691088:
Zrng(73) = 119025595:  Zrng(74) = 880802310:  Zrng(75) = 176192644:
Zrng(76) = 1116780070: Zrng(77) = 277854671:  Zrng(78) = 1366580350:
Zrng(79) = 1142483975: Zrng(80) = 2026948561: Zrng(81) = 1053920743:
```

```
Zrng(82) = 786262391:  Zrng(83) = 1792203830: Zrng(84) = 1494667770:
Zrng(85) = 1923011392: Zrng(86) = 1433700034: Zrng(87) = 1244184613:
Zrng(88) = 1147297105: Zrng(89) = 539712780:  Zrng(90) = 1545929719:
Zrng(91) = 190641742:  Zrng(92) = 1645390429: Zrng(93) = 264907697:
Zrng(94) = 620389253:  Zrng(95) = 1502074852: Zrng(96) = 927711160:
Zrng(97) = 364849192:  Zrng(98) = 2049576050: Zrng(99) = 638580085:
Zrng(100) = 547070247

End Sub

'*********************************************************************


Public Function Rand(Stream As Long) As Double

'Generate the next random number

    Dim Hi15 As Long
    Dim Hi31 As Long
    Dim Low15 As Long
    Dim Lowprd As Long
    Dim Ovflow As Long
    Dim Zi As Long

        Const B2E15 As Long = 32768
        Const B2E16 As Long = 65536
        Const Modlus As Long = 2147483647
        Const Mult1 As Long = 24112
        Const Mult2 As Long = 26143

        Zi = Zrng(Stream)
        Hi15 = Fix(Zi / B2E16)
        Lowprd = (Zi - Hi15 * B2E16) * Mult1
        Low15 = Fix(Lowprd / B2E16)
        Hi31 = Hi15 * Mult1 + Low15
        Ovflow = Fix(Hi31 / B2E15)
        Zi = (((Lowprd - Low15 * B2E16) - Modlus) + _
             (Hi31 - Ovflow * B2E15) * B2E16) + Ovflow

        If Zi < 0 Then Zi = Zi + Modlus
        Hi15 = Fix(Zi / B2E16)
        Lowprd = (Zi - Hi15 * B2E16) * Mult2
        Low15 = Fix(Lowprd / B2E16)
        Hi31 = Hi15 * Mult2 + Low15
        Ovflow = Fix(Hi31 / B2E15)
        Zi = (((Lowprd - Low15 * B2E16) - Modlus) + _
            (Hi31 - Ovflow * B2E15) * B2E16) + Ovflow

        If Zi < 0 Then Zi = Zi + Modlus
        Zrng(Stream) = Zi
        Rand = (2 * Fix(Zi / 256) + 1) / 16777216#

End Function

'*********************************************************************
```

```
Public Function Weibull(Beta As Double, Eta As Double, Stream As Long)
As Double

    Dim U As Double

        U = Rand(Stream)
        Weibull = Eta * (-1# * Log(U)) ^ (1# / Beta)

End Function

'*********************************************************************
```

```
Public Function Exponential(Lambda As Double, Stream As Long) As Double

Dim U As Double

        U = Rand(Stream)
        Exponential = (-1# / Lambda) * Log(U)

End Function

'*********************************************************************
```

```
Public Function Triangular(min, mode, max As Double, Stream As Long) As
Double

Dim U As Double
Dim c As Double
Dim X As Double

        c = (mode - min) / (max - min)
        U = Rand(Stream)

        If U <= c Then
            X = Sqr(c * U)
        Else
            X = 1 - Sqr((1 - c) * (1 - U))

        End If

        Triangular = min + (max - min) * X

End Function

'*********************************************************************
```